Theodolite and total station measurements of creep rates on San Francisco Bay region faults

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INVESTIGATIONS UNDERTAKEN

During the grant period from October 1, 2004 through September 30, 2005, we have continued to measure aseismic slip (i.e., creep) on San Francisco Bay region faults, extending a project that was begun by Jon Galehouse in 1979 (Galehouse, 2002; Galehouse and Lienkaemper, 2003). At each measurement site, we determine the amount of strike-slip movement within a width of about 55-280 m across faults to provide long-term observations about creep behavior and unusual or noteworthy fault movement. Monitored faults include the San Andreas, Hayward, Calaveras, Concord-Green Valley, Maacama, Rodgers Creek, and San Gregorio-Seal Cove faults (Figs. 1–7). The surveying is largely conducted by undergraduate Research Assistants under the supervision and training of several long-term project employees and the Principal Investigators. We presently collect regular measurements at 30 localities along alinement arrays on active faults, and have data from additional sites that have had to be abandoned (Table 1). We are continuing to re-measure most sites with a history of creep about once every eight to ten weeks and most sites without any creep history about every three to four months.

In addition to our ten regular sites on the Hayward fault, we annually measure 23 other Hayward sites in conjunction with J. Lienkaemper of the USGS. Jon Galehouse began measuring these additional sites in 1994, and our team completed its fifth collaborative set of measurements in October 2005. The team also monitors three additional sites on the northern Calaveras fault with J. Lienkaemper. Detailed information about the fault creep alinement arrays and measurement procedures can be found in Galehouse et al., 1982. We have created a new web site that includes the following information: project description, project personnel, creep characteristics and measurement, map of creep measurement sites, and creep site table with data plots and site descriptions. The web site makes our results accessible to anyone in the scientific community and to the general public; site URL: http://virga.sfsu.edu/creep/.

RESULTS

San Andreas fault: The three northernmost sites (Point Arena—SA1 to South San Francisco—SA3; Fig. 2A) continue to show no detectable creep, whereas the southernmost site near San Juan Bautista (SA7; Fig. 2B) continues to show an average creep rate of 12.8 mm/yr. A new site near Aromas (SA5; Fig. 2B) that was established to more precisely define the transition between the creeping and non-creeping segments, shows no detectable creep, consistent with previously recorded data at SA6 (Fig. 2B), a nearby site that was destroyed in a major landslide and hence abandoned in 1998. However, we have only a few years of data from SA5, so these results are preliminary. We carefully monitored data collected at SA4 in Woodside (Fig. 2A), which is located on what is considered a non-creeping segment of the San Andreas fault. This site shows little or no creep prior to 1998, but evidence of slow creep (1.2 mm/yr) from 1998 through 2004. In 2005, creep on the fault relaxed and rates returned to previously seen values. We will continue to closely watch this site, as well as the San Juan Bautista site (SA7), where the creep rate appears to have increased since 2004.

Hayward fault: The northern part of the Hayward fault (H1–H3 on Fig. 3A) continues to show creep rates ranging from 3.9–5.1 mm/yr. The southern part of the Hayward fault shows somewhat higher rates, ranging from 4.5–5.6 mm/yr (H5–H10 on Figs. 3B–3C). H4 (Fig. 3A) is located near the boundary between the northern and southern segments of the Hayward fault, and continues to show the lowest creep rate (3.3 mm/yr) of our sites on the fault. Several of the central sites show increasing creep rates. H7 and H8 (Fig. 3B) appear to show a small rate of increase since 1993. The two southernmost sites at Fremont (H9 and H10; Fig. 3C) ceased creeping for 6 years after the Loma Prieta earthquake, and then resumed creeping at a rate similar to the other Hayward fault sites. Creep rate at H9 may have increased slightly since 2003 (Fig. 3C). In addition to our ten regular Hayward fault sites, we continue to measure once each year 23 additional after-slip sites that were established in conjunction with J. Lienkaemper and that are used to document in detail any surface slip that could result from future seismic events (Lienkaemper et al., 2001).

Calaveras fault: Our sites on the Calaveras fault show mostly unchanging creep patterns for the past few years. Creep rates are highly variable between sites, ranging from 1.6–16.1 mm/yr (Fig. 4A). Creep at the northernmost site (CV1 in San Ramon; Fig. 4A) initiated in 1992. Creep rate at this site averaged about 3.5 mm/yr after 1992 but has apparently slowed to about 1.6 mm/yr since 2001. We observed no unusual behavior in association with the earthquake swarm in February 2003. CV3 (Fig. 4A) continues to be our fastest creeping fault, with an average rate of 16.1 mm/yr since 1968. CV3 may have slowed slightly since 1997, but the higher creep rate before 1997 is based on just a few measurements that were collected between 1968 and 1997 by others outside of our project. As with the southern section of the Hayward fault, creep rates on the southern section of the Calaveras fault slowed after the Loma Prieta earthquake, but returned to an apparently normal rate after 5–6 years (CV4 and CV5 on Fig. 4B). Since 1996, CV5 has developed a distinct pattern of episodic creep with intervals of no creep or very low creep rates between creep episodes (Fig. 4B).

Concord-Green Valley fault: In January 2005, we established a new Green Valley fault site (GV2) on Mason Road near Cordelia Junction. Only three readings have been made at this site and no conclusions can yet be drawn from the available data. The Concord-Green Valley sites (C1–C2, GV1) continue to show consistent creep rates of 3.1–4.2 mm/yr (Fig. 5). GV1 exhibits significant site noise, probably due to seasonal effects. This site was reconfigured in 1999 for logistical reasons, after which it began to show an even higher level of noise. We recently reconfigured the site again, and the preliminary measurements now seem to show a stronger (i.e., less noisy) creep signal. Creep at both sites on the Concord fault continues to show episodic behavior with 3–5 yr intervals between creep events. A 7-9 mm creep event occurred at the C1 site in late 2003. This event marks the shortest interval yet recorded between creep events (~3 yrs) at these sites (Fig. 5).

Maacama fault: Our sites on the Maacama fault continue to show creep rates of 4.3–6.1 mm/yr (Fig. 6). The creep rate at the site in Ukiah (M2 on Fig. 6) has slowed slightly since 2002 and we are watching this fault carefully for any further indications of unusual behavior.

Rodgers Creek fault: We now have several years of readings from our new sites on the Rodgers Creek fault (Fig. 6). Our initial readings over the past two years at the Santa Rosa site (RC1 on Fig. 6) showed a consistent creep rate of 3.6 mm/yr; however, after 14 readings at the site we obtain a rate of 1.8 mm/yr. Our other new site on the Rodgers Creek fault at Sonoma Mountain Road in Petaluma (RC2 on Fig. 6) was reconfigured after it seemed we were measuring downslope soil creep rather than fault creep. Our first measurements at the reconfigured site suggested rapid creep but after only 7 readings the measured creep rate is decreasing, and the results are still highly preliminary.

San Gregorio-Seal Cove fault: Sites on the San Gregorio-Seal Cove fault continue to have rather noisy signals, but consistent trends. The SG1 site on the Seal Cove fault (Princeton; Fig. 7) continues to show no indication of creep. However, readings at the SG2 site on the San Gregorio fault (Pescadero Road; Fig. 7) from 2001 to 2004 seemed to indicate a creep rate of 5.8 mm/yr since 2002, compared to a rate of 0.6 mm/yr prior to 2002. In 2005, the creep rate diminished and rates on the San Gregorio fault at SG2 are returning to those seen previously. We are watching this site carefully, however, particularly as there appears to have been a similar slight acceleration on the nearby San Andreas fault (Woodside site SA4; Fig. 2A).

NEW ALINEMENT ARRAY SITES

Two new alinement array sites were installed in 2005. In January 2005, GV-2 was installed across the Green Valley fault on Mason Road near Cordelia Junction, California. Data are still in the preliminary stage. In November 2005, BS-1 was installed across the

Bartlett Springs fault near Lake Pillsbury, California. Only an initial reading has been made; however, geomorphic evidence at the site, including well-developed, left-stepping en-echelon cracks, suggest the possibility of creep motion.

PROPOSED NEW ALINEMENT ARRAY SITES

We are looking into the feasibility of establishing two new sites this upcoming year. One would be a locality on the Sargent fault, and another would be an additional site on the Green Valley fault to replace the problematic GV-1 site.

DATA ANALYSIS AND DISSEMINATION

We have begun to develop analytical and interpretive phases of the project that will involve the P.I.s with undergraduate and graduate student research. For example, we are conducting a comprehensive analysis of how details of the creep signal for the different faults compare to temporal variations in microseismicity along the faults at creep measurement sites (Mascorro, in preparation; Mascorro, et al., 2005).

In addition to disseminating our fault creep data via reports to NEHRP (e.g., Grove and Caskey, 2005), we have also created a web site with information about the fault creep project. The web site makes our results accessible to anyone in the scientific community and to the general public; site URL: http://virga.sfsu.edu/creep/. At any time, information about the project can be requested via email: fltcreep@sfsu.edu.

CONCLUSIONS

Readings from most fault sites continue to show consistent patterns of creep, ranging from no creep on the northern San Andreas fault to a maximum of 16.1 mm/yr on the southern Calaveras fault. Any changes to the observed creep rates must be evaluated carefully, to be certain that measurements are indicating fault creep rather than seasonal effects, soil creep, or other non-tectonic signals. We now have sufficient data to suggest that several observed changes are due to creep that may be significant.

1. Northern Calaveras fault (CV1 on Fig. 4A): deceleration of creep rate since 2002 (3.5 mm/yr before 2001; 1.6 mm/yr since 2001).
2. Rodgers Creek fault (RC1 on Fig. 6): first reported right-lateral creep on this fault. Movement has averaged 1.8 mm/yr since we established the site in 2002; second site RC2 (Fig. 6) remains preliminary.
3. San Gregorio fault (SG2 on Fig. 7): after no indication of creep from 1982–2002, an apparent increase in 2002, followed by a decrease in 2005 (nearby SA4 site also showed increases followed by recent decrease).

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Mascorro, M.T, Caskey, S.J., and Lienkaemper, J.J., 2005, Relations between fault creep and microseismicity along strike-slip faults in the San Francisco Bay area, EOS Transactions, Am. Geophys. Union.

NON-TECHNICAL SUMMARY

We are measuring the rate of aseismic slip (i.e., creep) at 30 sites that cross faults in the seismically active San Francisco Bay region. Our primary purpose is to determine the rates of present fault movement and to discover any changes that might occur before, during, or after a seismic event

DATA AVAILABILITY

Creep data collected from all of our sites between 1979 and 2001 are available online in Open-File Report 02-225 (http://geopubs.wr.usgs.gov/open-file/of02-225/) and in the 2001 NEHRP Final Technical Report (http://erp-web.er.usgs.gov/reports/annsum/vol42/nc/g0084.htm)

Data collected through 2005 are available on the project web site: http://virga.sfsu.edu/creep/

For additional information about our creep data, please contact either Karen Grove, 415-338-2617, kgrove@sfsu.edu; John Caskey, 415-405-0353, caskey@sfsu.edu; or Forrest McFarland (Project Manager for day-to-day operations), fltcreep@sfsu.edu.

Table 1. San Francisco State University Theodolite Measurement Sites

Fault (# on Figs.2-7)	Location (# on Fig. 1)	First Measurement	Fault Width Span (m)
San Andreas (SA1)	Alder Creek in Point Arena area (#18)	1981.025	267.4
San Andreas (SA2)	Olema at Point Reyes National Seashore (#14)	1985.096	70.6
San Andreas (SA3)	Duhallow Way in South San Francisco (#10)	1980.227	205.8
San Andreas (SA4)	Roberta Drive in Woodside (#22)	1989.844	91.2
San Andreas (SA5)	Searle Rd., San Juan Bautista (#37)	2002.799	262.7
San Andreas[1]	Pajaro Gap at Aromas (#38)	2002.107	236.3
San Andreas (SA6)[2]	Cannon Road near San Juan Bautista (#23)	1989.882	88.0
San Andreas (SA7)	Mission Vineyard Rd, San Juan Bautista (#25)	1990.553	134.2
Hayward (H1)	Contra Costa College in San Pablo (#17)	1980.609	106.8
Hayward (H2)	Thors Bay Road in El Cerrito (#34)	1989.748	120.0
Hayward[3]	Florida Avenue in Berkeley (#30)	1993.112	73.6
Hayward (H3)	LaSalle Avenue in Oakland (#29)	1993.112	182.5
Hayward (H4)	Encina Way in Oakland (#28)	1993.058	105.4
Hayward (H5)	Rose Street in Hayward (#13)	1980.481	153.9
Hayward (H6)	D Street in Hayward (#12)	1980.478	136.2
Hayward (H7)	Appian Way in Union City (#2)	1979.729	125.2
Hayward (H8)	Rockett Drive in Fremont (#1)	1979.726	180.0
Hayward (H9)	Camellia Drive in Fremont (#24)	1990.115	88.6
Hayward (H10)	Parkmeadow Drive in Fremont (#27)	1992.262	157.4
Calaveras (CV1)	Corey Place in San Ramon (#19)	1980.896	111.1
Calaveras (CV2)	Welsh Creek Road and Calaveras Road (#32)	1997.066	164.1
Calaveras (CV3)	Coyote Ranch near Coyote Lake (#33)	1972.570	101.3
Calaveras (CV4)	Wright Road near Hollister (#6)	1979.805	103.4
Calaveras (CV5)	Seventh Street in Hollister (#4)	1979.745	89.7
Concord (C1)	Salvio Street in Concord (#5)	1979.748	57.1
Concord (C2)	Ashbury Drive in Concord (#3)	1979.742	130.0
Green Valley (GV1)	Watt Drive in Cordelia (#20)	1984.456	335.8
Green Valley (GV2)	Mason Road in Cordelia Junction	2005.060	
Maacama (M1)	West Commercial Avenue in Willits (#26)	1991.871	126.1
Maacama	Sanford Ranch Road near Ukiah (#31)	1993.389	263.2
Rogers Creek (RC1)	Solano Dr. in Santa Rosa (#36)	2002.628	90.5
Rogers Creek (RC2)	Sonoma Mt. Rd., in Petaluma (#35)	2002.628	99.4
Rodgers Creek[4]	Nielson Road in Santa Rosa (#16)	1980.628	209.1
Rodgers Creek[5]	Roberts Road near Penngrove (#21)	1986.721	198.7
Seal Cove (SG1)	West Point Avenue in Princeton (#7)	1979.858	266.6
San Gregorio (SG2)	Pescadero Road near Pescadero (#8)	1982.384	455.0
Antioch[6]	Deer Valley Road near Antioch (#9)	1982.890	226.2
Antioch[7]	Worrell Road in Antioch (#11)	1980.342	103.9
West Napa[8]	Linda Vista Avenue in Napa (#15)	1980.568	130.9

[1]Site abandoned soon after established for safety reasons.
[2]Site abandoned for logistical reasons. Last measurement 1998.123.
[3]Replaced by H2 as regular measurement site.
[4]Site abandoned for logistical reasons. Last measurement 1986.055.
[5]Site abandoned for logistical reasons.
[6]Site abandoned for logistical reasons. Last measurement 1990.499.
[7]Site abandoned for logistical reasons. Last measurement 2000.158.
[8]Site abandoned for logistical reasons. Last measurement 1999.044.

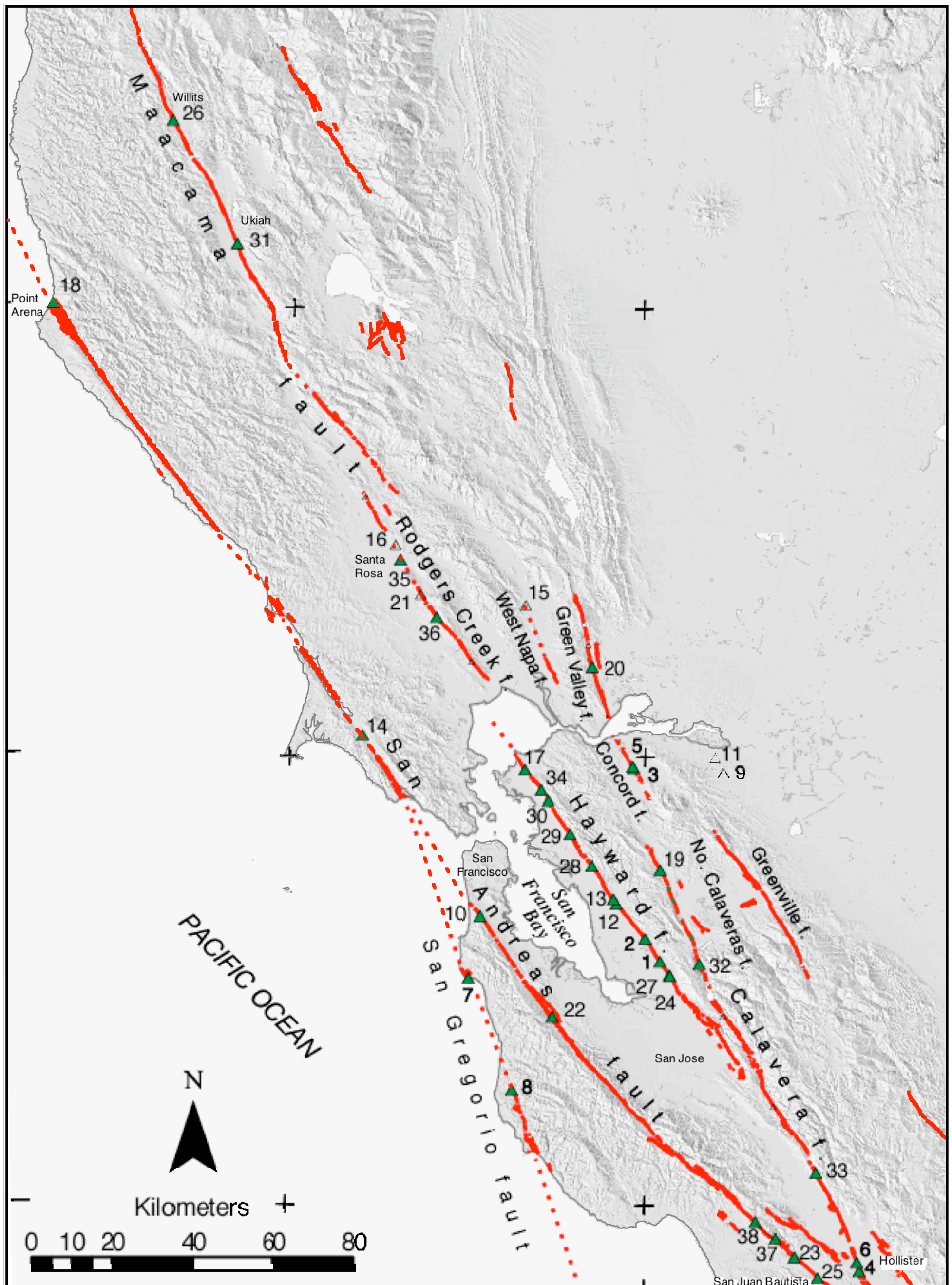


Figure 1. Numbered triangles are San Francisco State University theodolite and total-station creep measurement sites on active Bay Region faults.

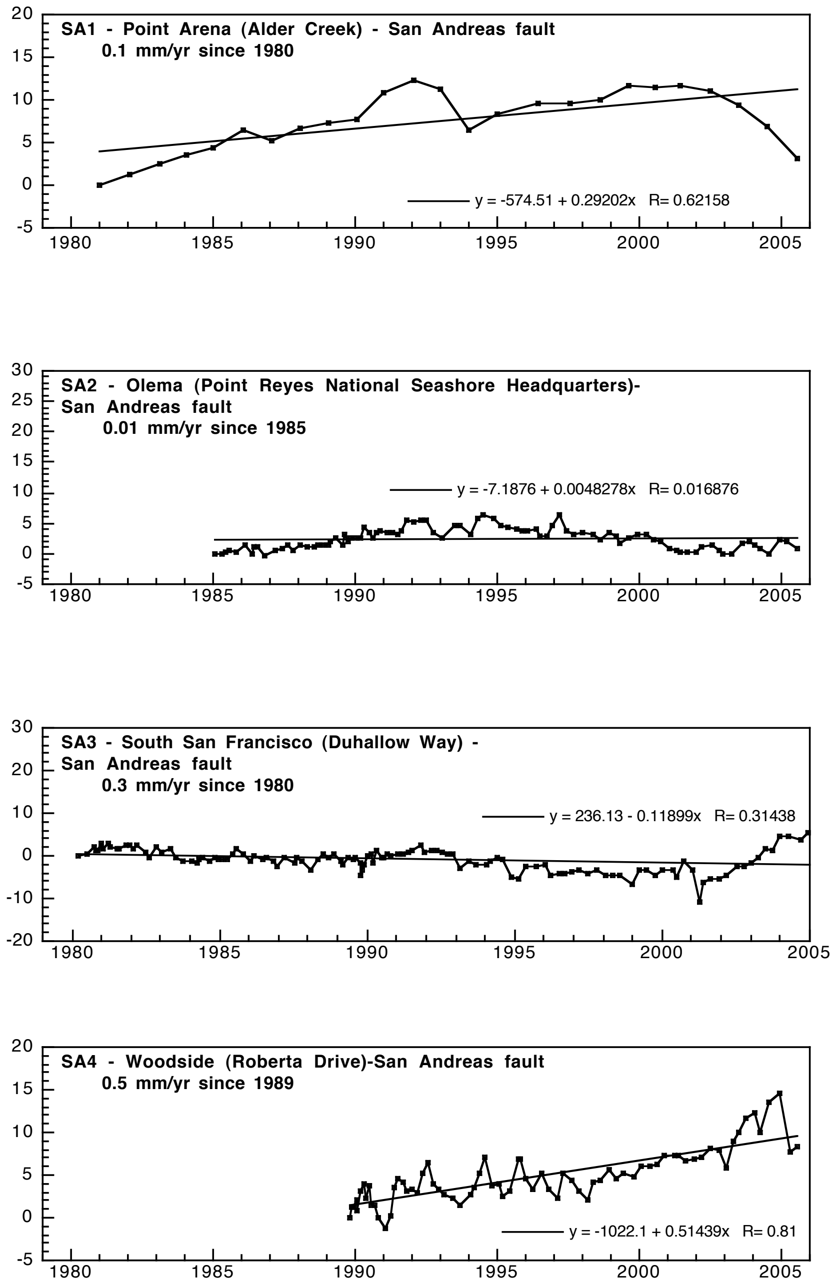


Figure 2A. San Andreas fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

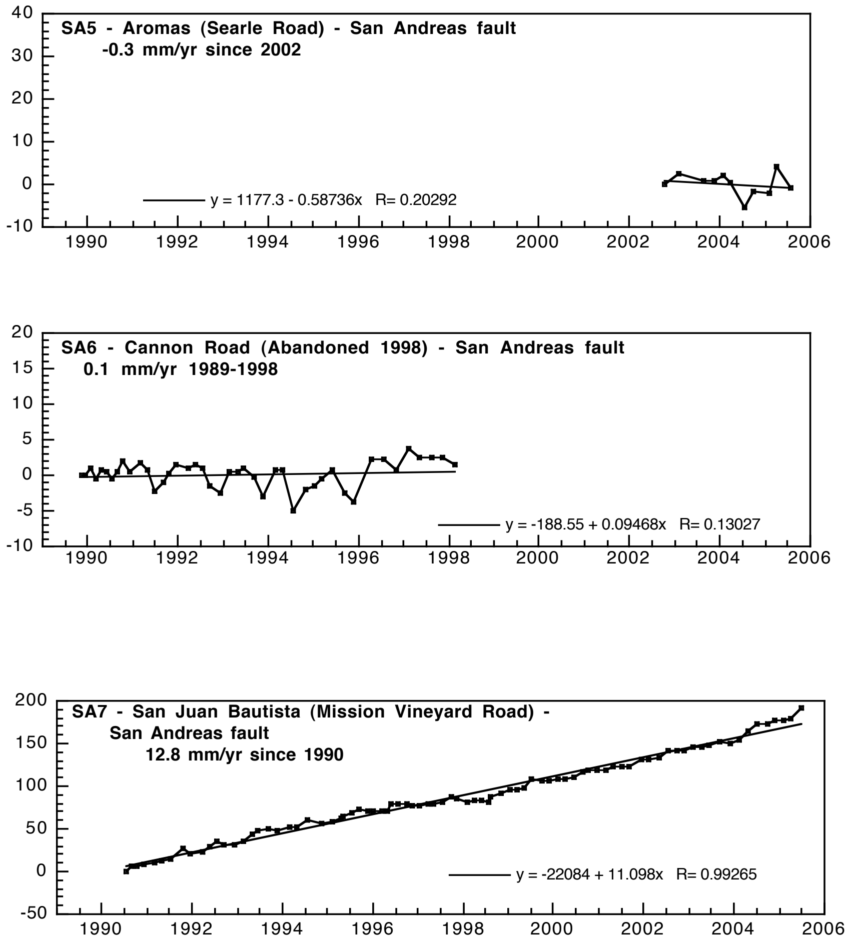


Figure 2B. San Andreas fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note change in vertical scale for SA7.

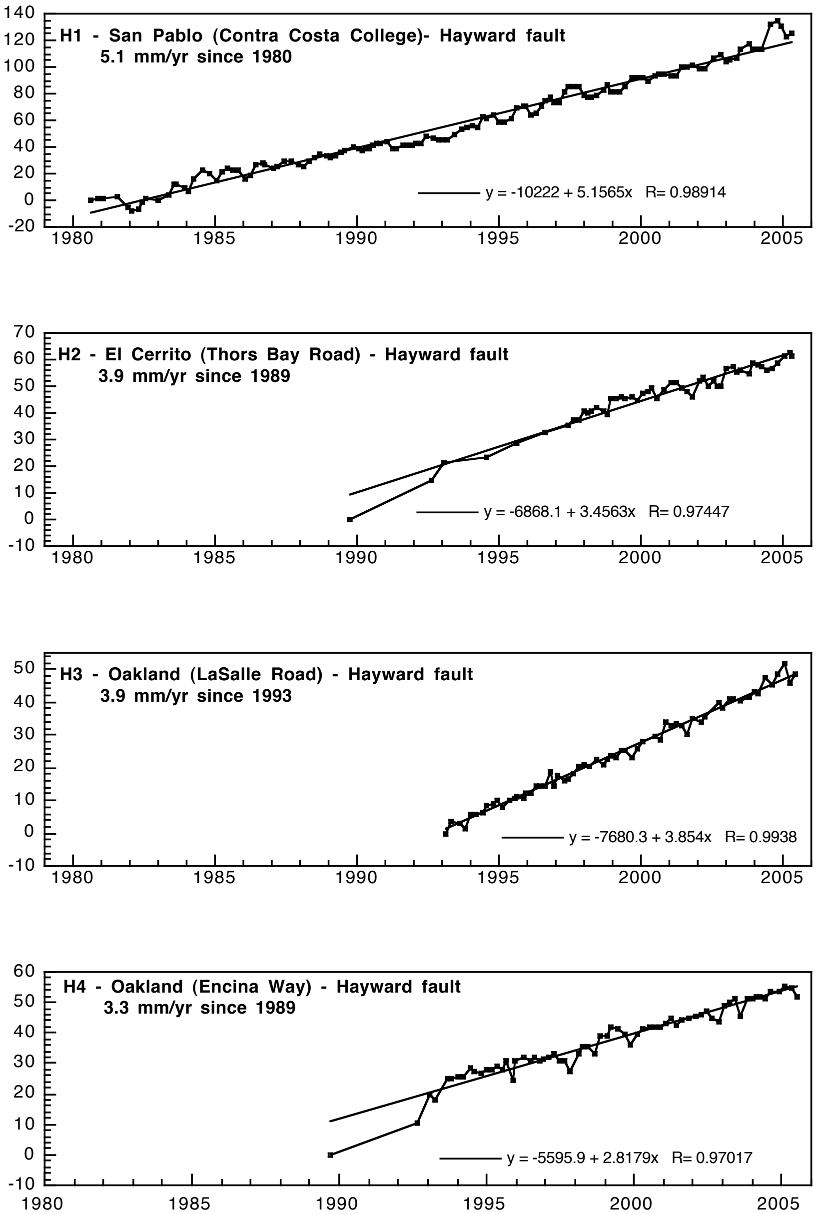


Figure 3A. Hayward fault north surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

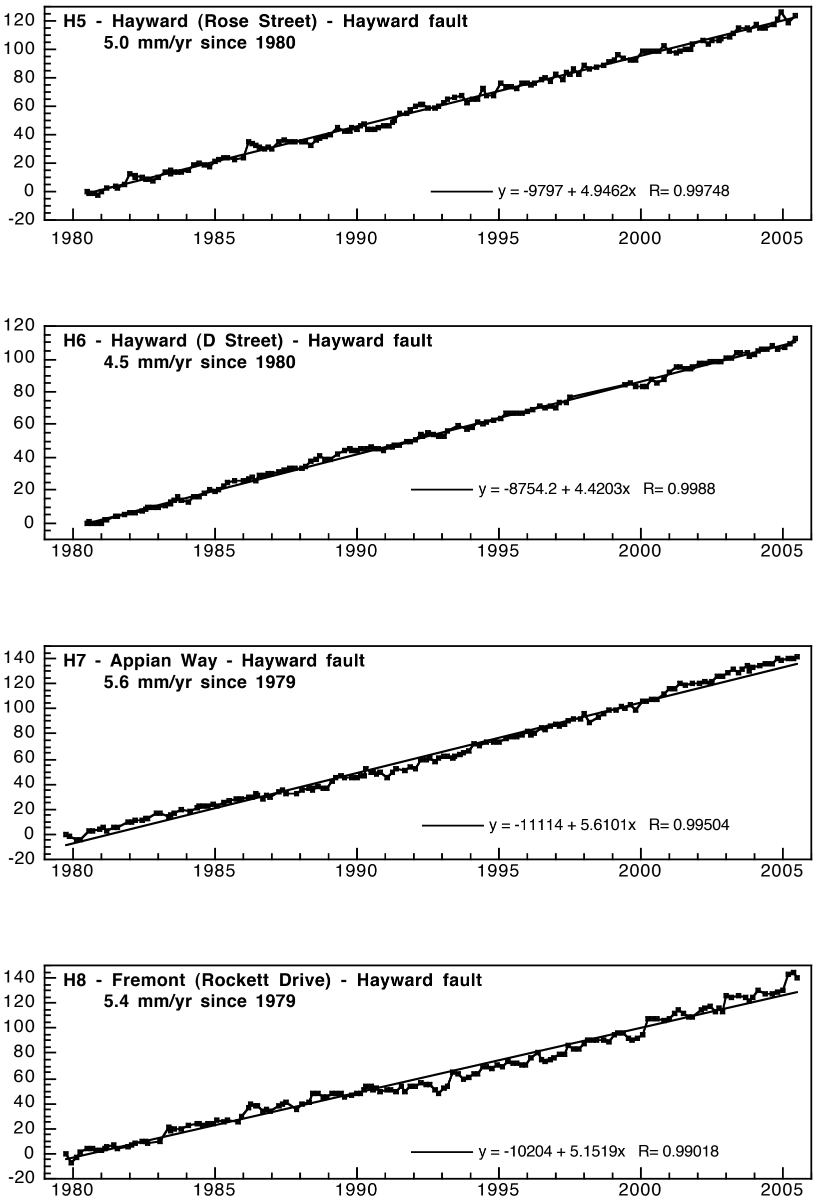
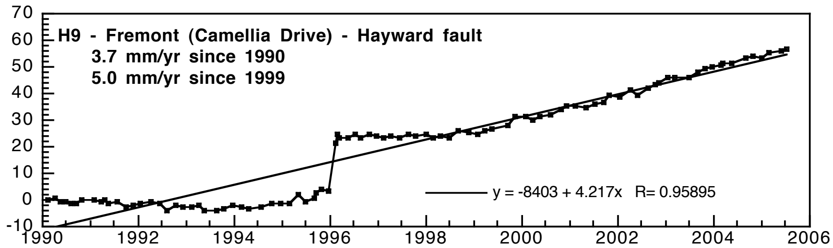


Figure 3B. Hayward fault south surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.



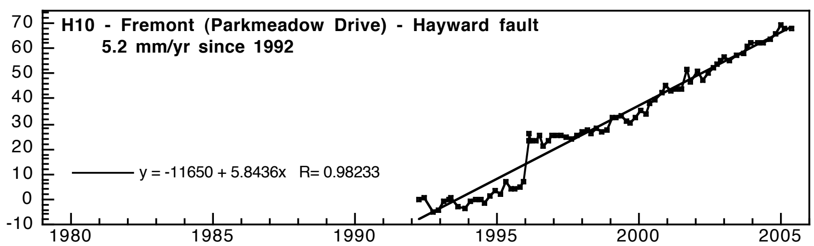


Figure 3C. Hayward fault south surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

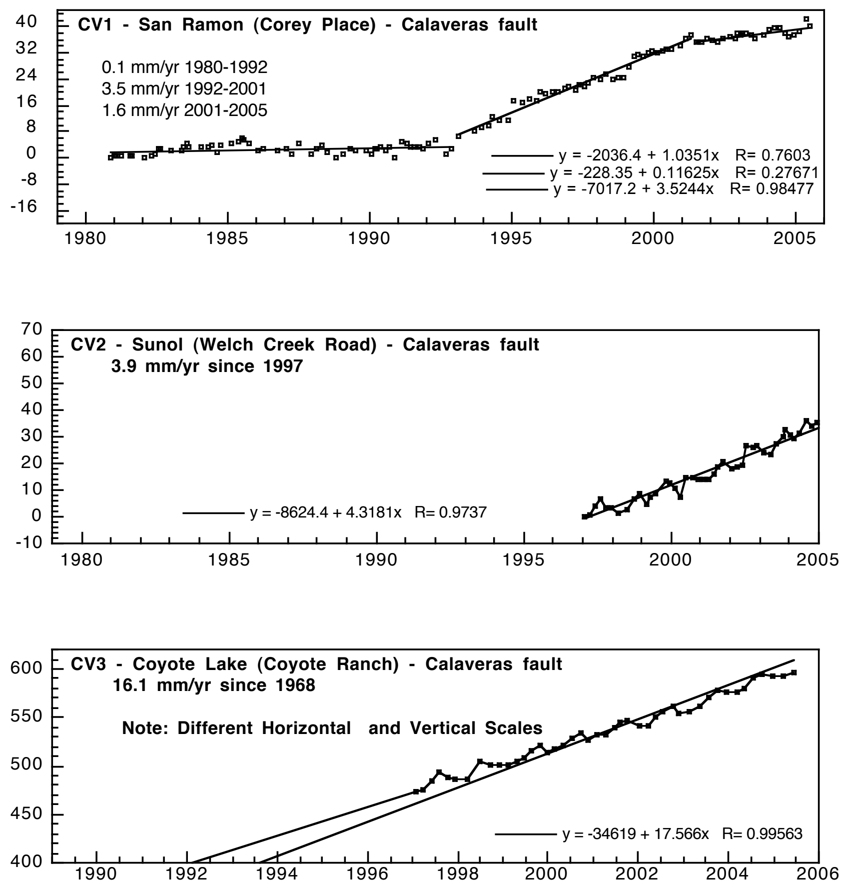


Figure 4A. Calaveras fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

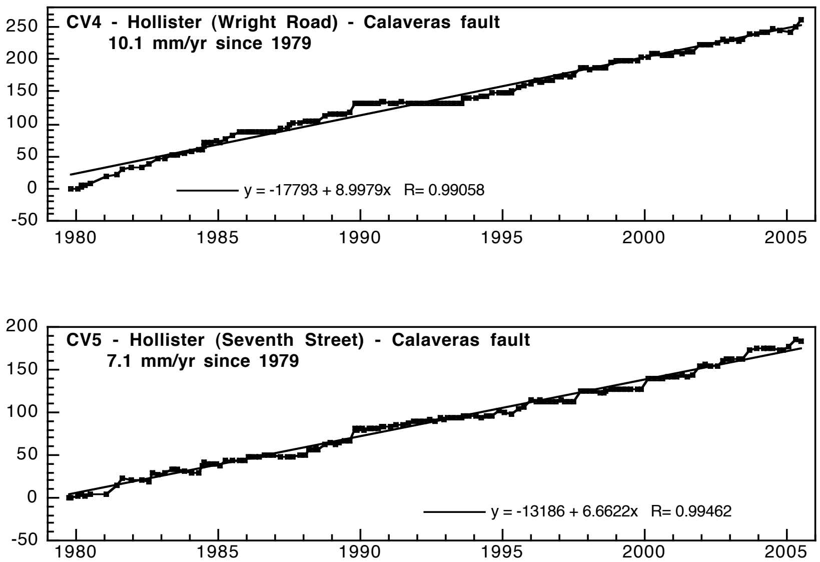


Figure 4B. Calveras fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

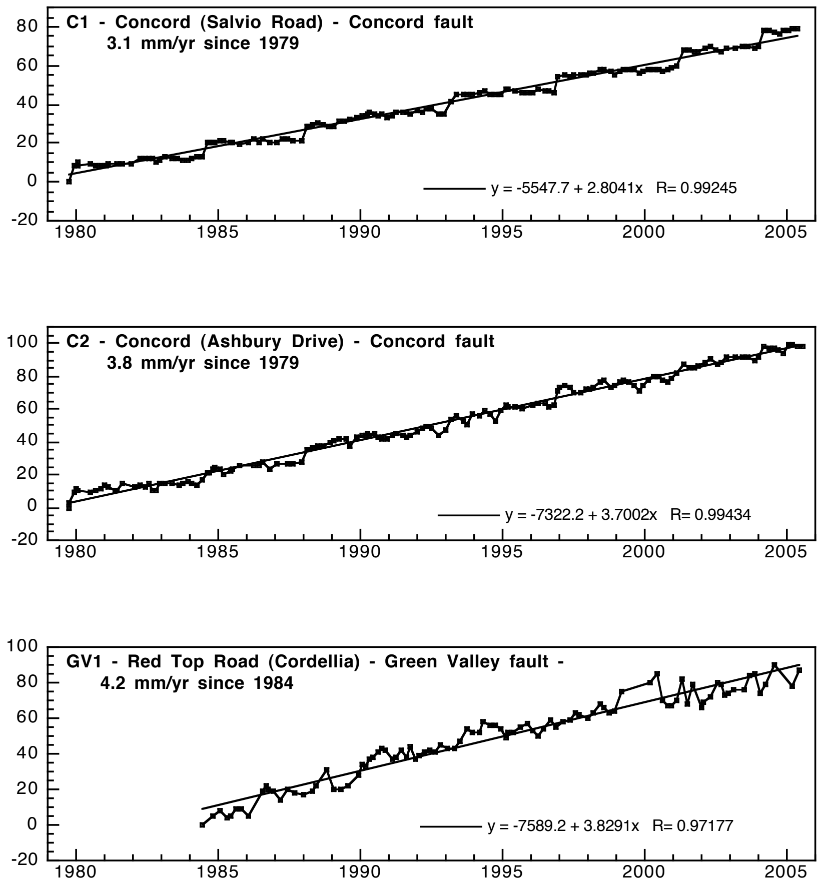


Figure 5. Concord–Green Valley fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

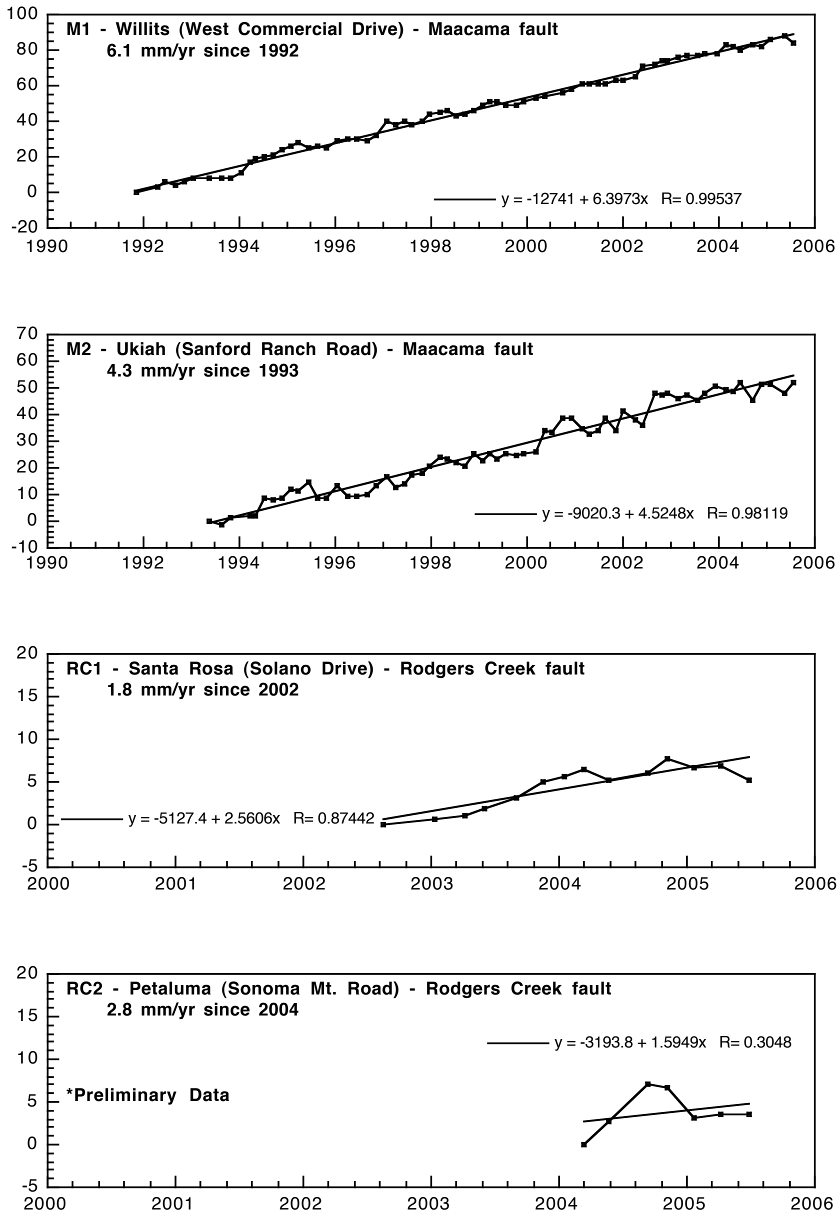


Figure 6. Maacama and Rodgers Creek faults surface displacement from 1990–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

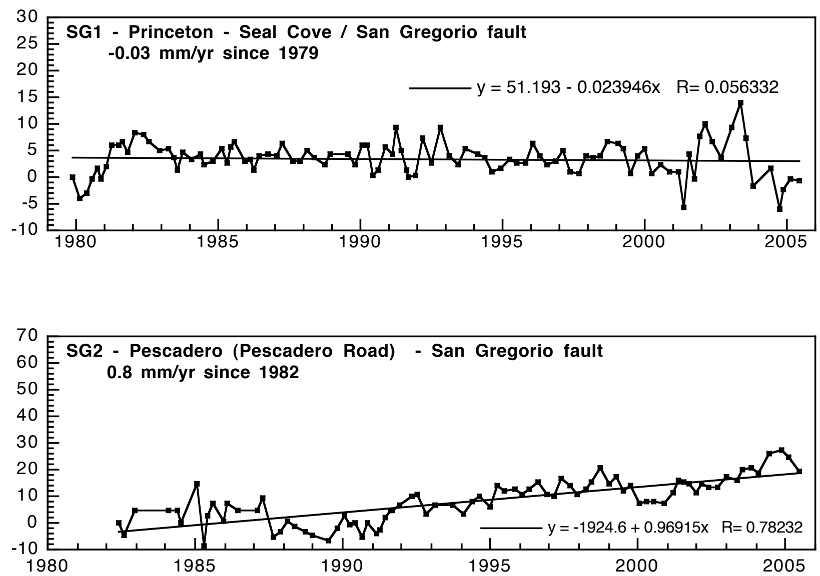


Figure 7. Seal Cove–San Gregorio fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.